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Contents

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Introduction

White pine blister rust limits the reproduction of white pine in many areas by killing young trees. In other extensive areas unjustified fear of the disease limits white pine planting. An ability to differentiate the sites on which white pine blister rust (caused by Cronartium ribicola Fischer) might be serious from those on which the disease might cause little damage would be of great value. Sites on which rust will not spread seriously could be recommended for the planting of eastern white pine (Pinus strobus L.) without the expense of eradicating nearby ribes bushes. Likewise, funds need not be spent for ribes control in existing white pine stands and nearby sites where severe damage is unlikely.

A contribution of the University of Wisconsin, Wisconsin Conservation Department, and the U.S. Forest Service cooperating. The work reported in this paper was done while Van Arsdel was a Research Assistant at the University of Wisconsin with Wisconsin Conservation Department support. He now is a Plant Pathologist of the Lake States Forest Experiment Station and stationed at the University of Wisconsin. The Lake States Forest Experiment Station is maintained at St. Paul 1, Minn., by the Forest Service, U.S. Department of Agriculture, in cooperation with the University of Minnesota. Riker is Professor of Plant Pathology, University of Wisconsin. Kouba was formerly area leader, U.S. Forest Service, Forest Pest Control, Madison, Wis.; is now Forester, Cooperative Forestry, U.S. Forest Service, Regional Office, Milwaukee. Suomi and Bryson are Professors of Meteorology, University of Wisconsin. The authors appreciate the help of Peter Kuhn, Research Meteorologist, U.S. Weather Bureau, at the University of Wisconsin.

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The importance of climate in the epidemiology of plant diseases has long been recognized. It was early realized, for example, that blister rust spread much more rapidly in cool, moist northwestern Europe than it did in parts of New England (Spaulding 1929). Reviews of the spread of blister rust in other places have shown limited spread in areas of high temperatures and low humidities (Boyce 1948). The rate of spread shown by distribution maps was rapid in the northern United States while infections in southern areas remained static (Spaulding 1922). Differences in the frequency of blister rust on white pine have also been noted in different parts of Wisconsin. In certain large areas in the southern part of the State white pines were generally free of infection even though ribes were common and rust has been continually present on the ribes bushes.

This situation, discussed by Van Arsdel et al. (1953), led to the study of the climatic limitations to the spread of blister rust. A further study by Van Arsdel et al. (1956) helped interpret the specific effects of temperature and moisture on the spread of the blister rust fungus. It showed that infection of the pine required specifically favorable conditions. In Wisconsin 2 weeks of cool weather, with less than 3 consecutive days (with 5-hour warm period) over 82° F. in the second week, were required to produce fertile teliospores. Once formed, these fertile teliospores were less susceptible to damage by high temperatures. When the temperatures for these 2 weeks were under 68° F. the germination of the teliospores was much greater. In general, the cooler the weather while ribes leaves carried active telia, the greater the chances for vigorous sporidia to reach the pines. Furthermore, pine infection required at least 48 hours with saturated air at less than 68° F. This temperature was chosen as a critical one in later studies.

A search of the weather records for Rhinelander and Madison, Wis., showed that in 25 years (1929-1953) weather considered favorable for rust infection occurred 12 times in Rhinelander but only 6 times in Madison. Rust infection weather occurred in July, August, or September in Rhinelander but only in September in Madison after ribes bushes commonly had defoliated. Thus the chances for rust infection in the Madison macroclimate seemed remote (Van Arsdel 1954).

The purpose of this paper is to present results of sampling historical and existing blister rust distribution in Wisconsin; to correlate local temperature and moisture conditions with topography and vegetative cover; to give explanations for local temperature and moisture distribution; and to correlate blister rust incidence with chances of favorable weather as influenced by local site characteristics, latitude, and overall climate. From these factors a means is suggested for describing and identifying sites favorable and unfavorable for development of serious blister rust infection on pines. Such descriptions may help to guide future white pine planting and ribes eradication work.

Survey methods and study areas

During 1951 to 1953 rust distribution was studied on 5 intensively sampled areas, on 20 areas less intensively sampled, and on 7 others, which were observed but not sampled. Microclimatic factors were studied on the 5 intensively sampled areas and on 1 other area near the Madison weather station in Dane County. On the basis of information collected in these surveys, a site value rust index was developed. In 1954 it was checked on 1 intensively sampled area and 30 less

intensively sampled ones. The areas varied in size; some had stands of pine covering as much as 100 acres, but the usual size was about 20 acres.

All the study areas are indicated by circles in figure 1 (page 4); those with the large circles are where climatic factors were studied. Figure 2 (page 5) shows the average July temperature and the topography and elevation for the State. A description of the study areas and of the data collected on them follows.

The first area was established in 1951 on a 55-acre woodlot of 50- to 70-foot oak trees in Rock County (Rock-1, figs. 1 and 3 on pages 4 and 6), southern Wisconsin. This glaciated area is level to rolling, and vegetation exerts the dominant influence on microclimate. The area had about 50,000 feet of live stem per acre of *Ribes missouriense* Nuttall, *R. cynosbati* L., and *R. americanum* Mill. No plots were established, but all 425 white pine trees, planted in groups in the woodlot from 1932 to 1938, were examined for blister rust cankers. Data were tabulated for the size (usually 15 to 30 feet tall) and vigor of each tree, the number of blister rust cankers per tree, the length of each canker, the year it was apparently initiated, the distance from the canker to the trunk, and the distance from the canker to the ground. The oldest rust infection found in this area was on 1937 wood; thus, the fungus had been present for at least 15 years when the data were collected.

To clarify the effects of topography and vegetation on rust distribution in the hilly, unglaciated country of southwestern Wisconsin, a 22-acre area in Iowa County (Iowa-1, figs. 1 and 4 on pages 4 and 7) was studied. It had an all-aged white pine stand (with trees up to 120 feet tall), including good reproduction, on St. Peters sandstone with various aspects and types of sites. Most calculations were based on 108 0.01-acre sample plots arranged at 1-chain intervals along strips 2½ chains apart. Two larger permanent plots were established to follow the progress of the rust.

This area had 3,800 feet of *R. cynosbati* and *R. missouriense* live stem per acre, well distributed. The small north-facing valley just to the right and above center in figure 4 was surrounded by trees to combine the effects of a valley and a forest opening. This valley was about 100 feet wide at the bottom and 265 feet wide between the crests of the containing ridges. The hills forming the valley slopes were about 50 feet high on the east and 40 feet high on the west. The trees on the east slope and crest were predominantly white oaks (*Quercus alba* L.) 60 to 70 feet tall, whereas those on the west crest were white pines 100 to 110 feet tall. Thus, the vegetation moderated the differences between hill heights. The deepest part of the valley from the fork at the head was 330 feet long, while the total length from the beginning of the north slope to the mouth at the road was 660 feet. The slope at the south end of the valley was steep. The ratio of the bottom width of the valley to the height of the walls was approximately 2.0, while the trees on the slopes and crests made a total W/H (width to height) ratio of about 1.33.

Another detailed study area in this hilly region was in Sauk County (Sauk-1, fig. 1). The white pine trees were in a natural, all-aged stand on slightly weathered Baraboo quartzite where Narrows Creek cuts southeast through part of the Baraboo range. Twenty-five 0.01-acre plots were taken at 1-chain intervals across the canyon. This transect is diagrammed in figure 5 (page 7). The canyon varied from 130 to 200 feet wide at the base and was 750 feet from shoulder to shoulder. It was approximately 290 feet from the bottom of the canyon to the

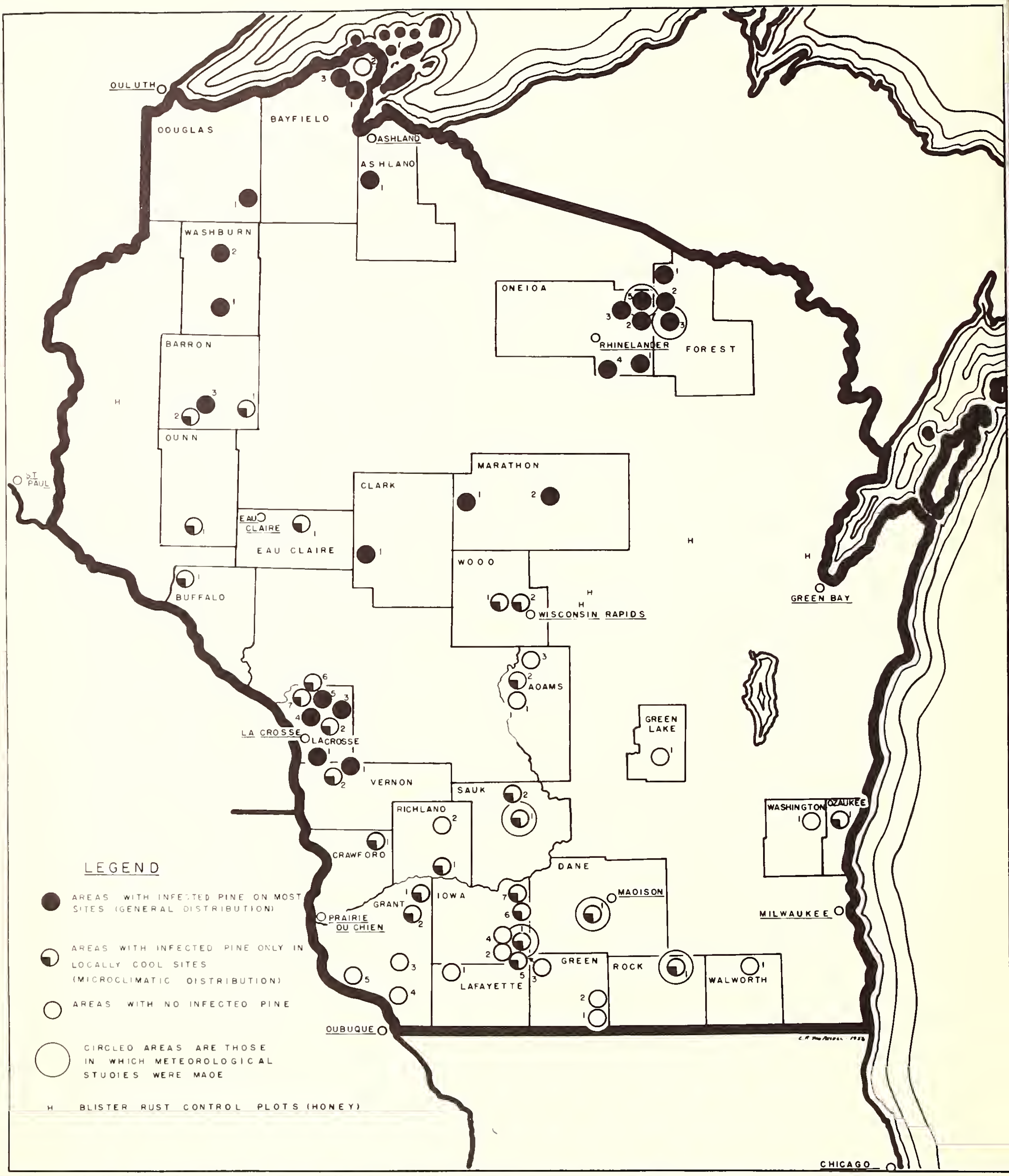

Figure 1.--Blister rust study areas in Wisconsin and the type of rust distribution found on each area.

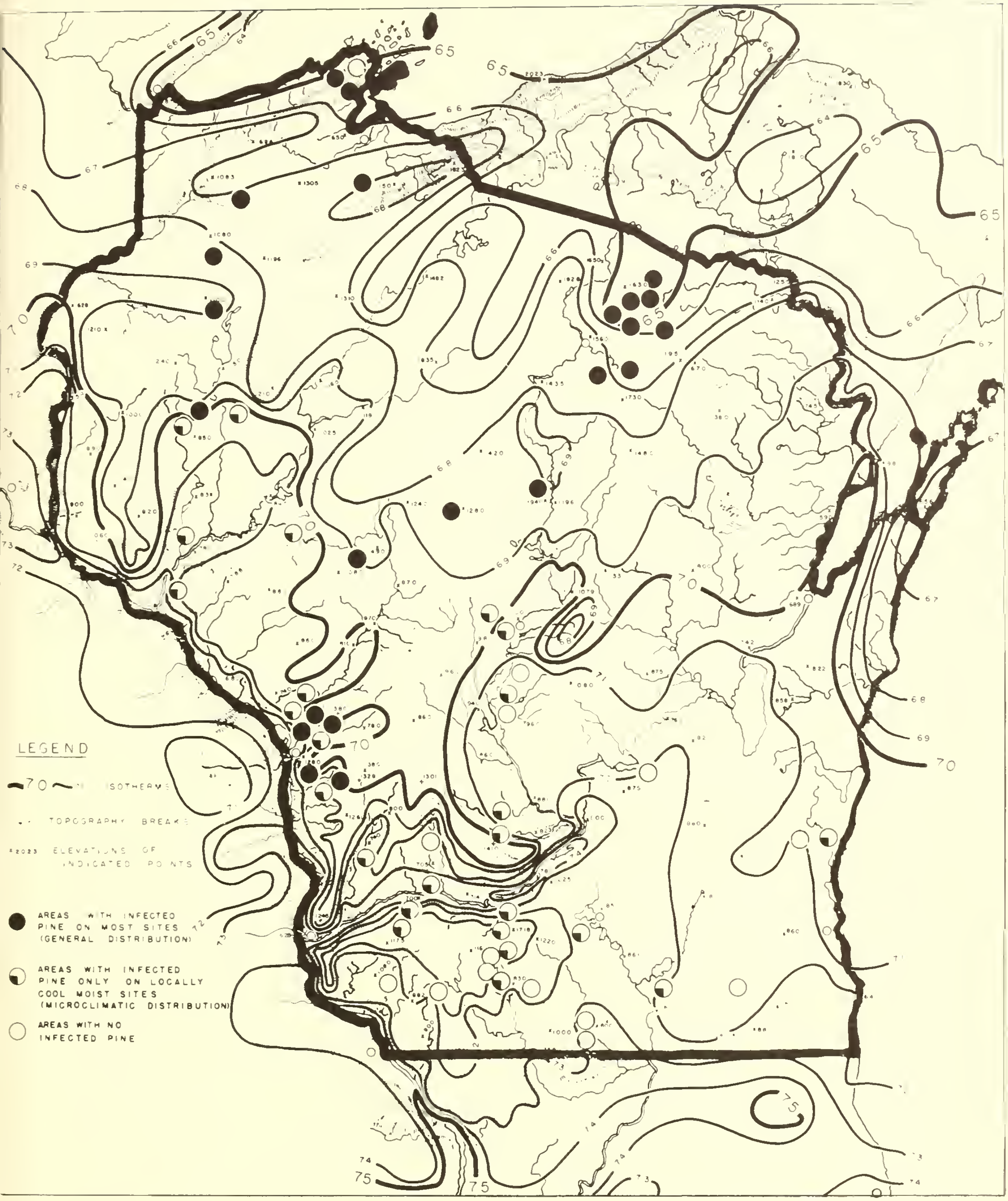

Figure 2.--Average July temperature (°F.), topography (hachures), and elevations (feet above sea level) superimposed on figure 1. Isotherms were spaced to follow natural topographic features between weather stations.

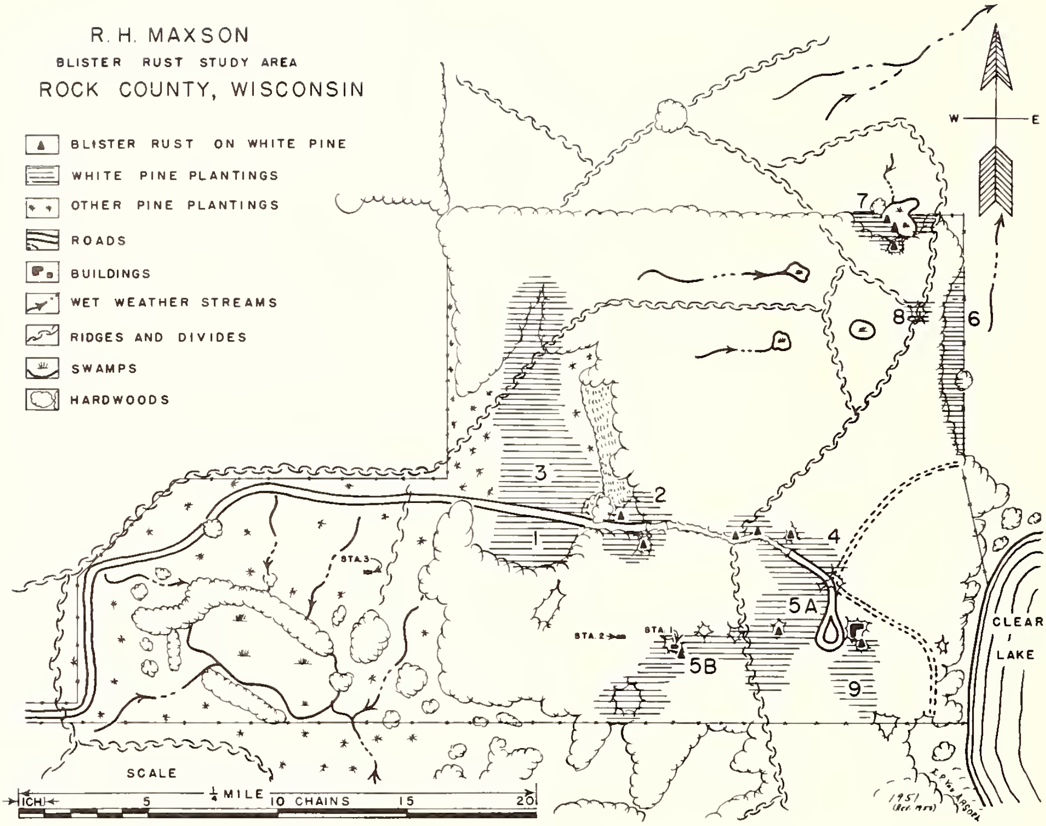

Figure 3.--Southern Wisconsin area in Rock County where blister rust distribution on white pine was studied (Rock-1, fig. 1). Small solid triangles indicate rust infection on pine.

crest of the southwest shoulder and 230 feet to the crest of the northeast shoulder. The ratio of the width of the bottom of the canyon to the height of the shoulders (W/H) was roughly 0.67. The shoulders of the canyon were exposed, and stunted trees at the edge did not affect the site materially. Since the stream that formed this canyon flowed from northwest to southeast, northeast and southwest exposures were dominant on the canyon walls.

In cooler northern Wisconsin the spread of rust was studied in some detail on two areas. In Oneida-5, 57 plots were examined. Figure 6 (page 8) indicates the variety of different sites. A gravel plateau 75 feet above the lowland dominated the area. Minor hills and kettle holes were present. Light (5 to 100 feet of live stem per acre) Ribes glandulosum were present in the swamps. Sample lines with plots every chain were started near the swamps with ribes and then led 1900 feet away from the ribes. Forest-3 was a brushy, low drumlin (rolling) area containing 28 plots.

Rust distribution was also assessed in less intensive sampling on 20 other areas distributed from north to south near the center of the State (fig. 1). In each of these, about ten 0.01-acre plots were taken.

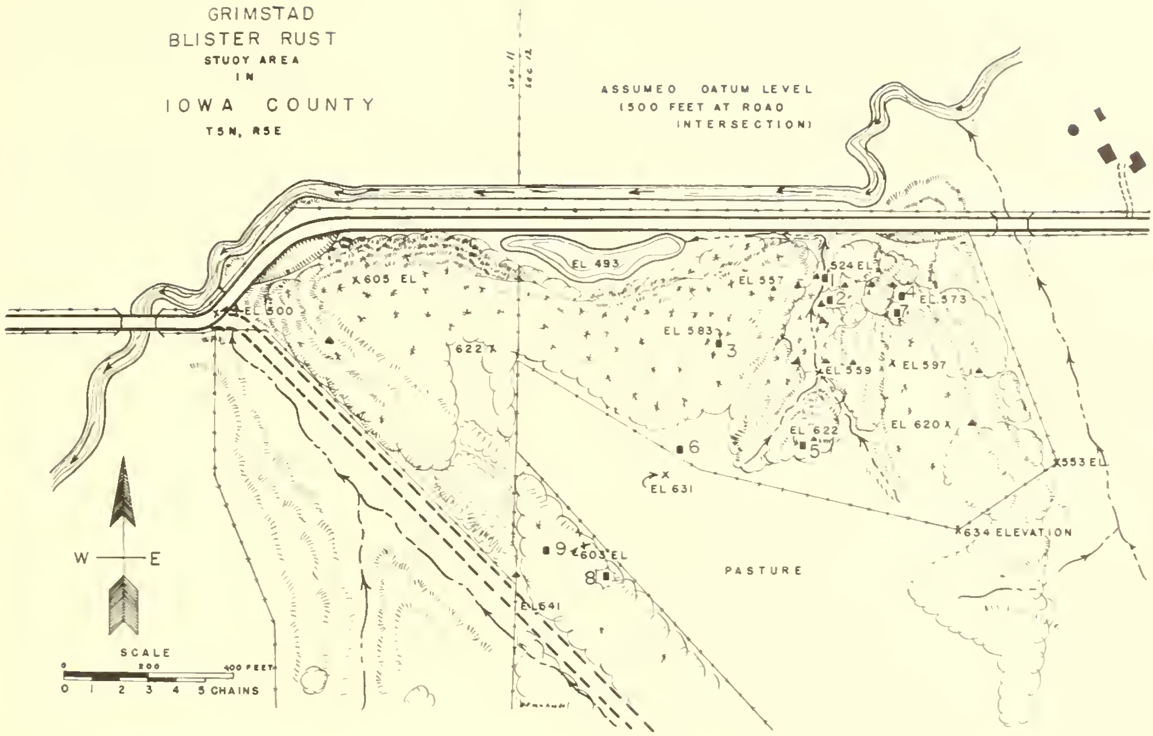

Figure 4.--Blister rust study area in hilly southeastern Iowa County (Iowa-1, fig. 1). Small solid squares are weather stations; small solid triangles are plots with blister rust present on pine.

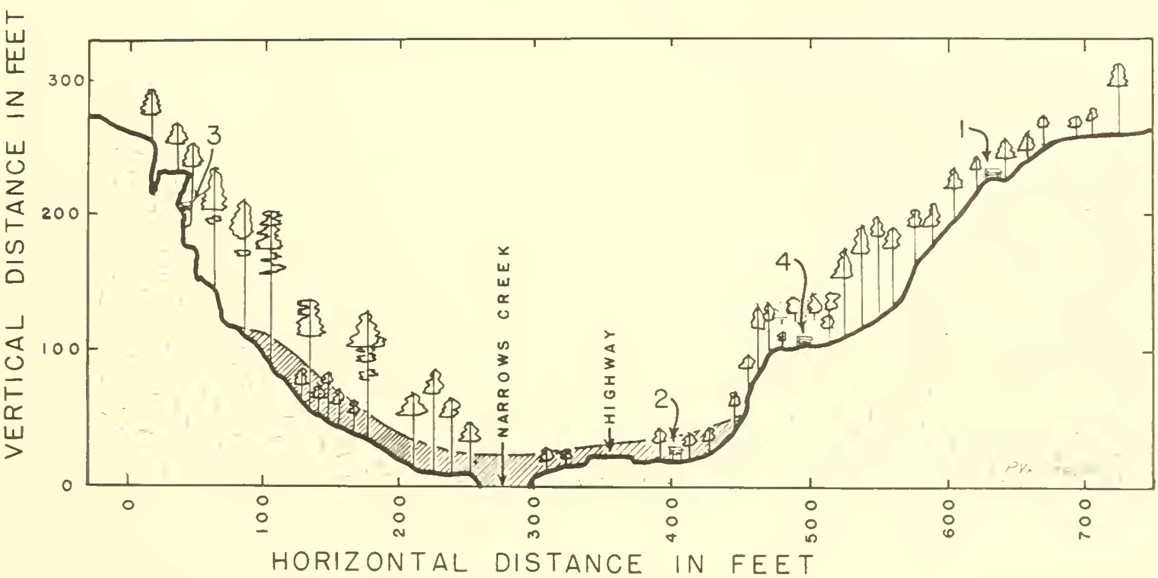

Figure 5.--Profile of Sauk County area (Sauk-1, fig. 1) with rust distribution and weather station locations. Shaded area indicates portion in which pines were infected; weather stations are numbered 1 to 4. Left side is the profile of the southwest shoulder; right side the northeast.

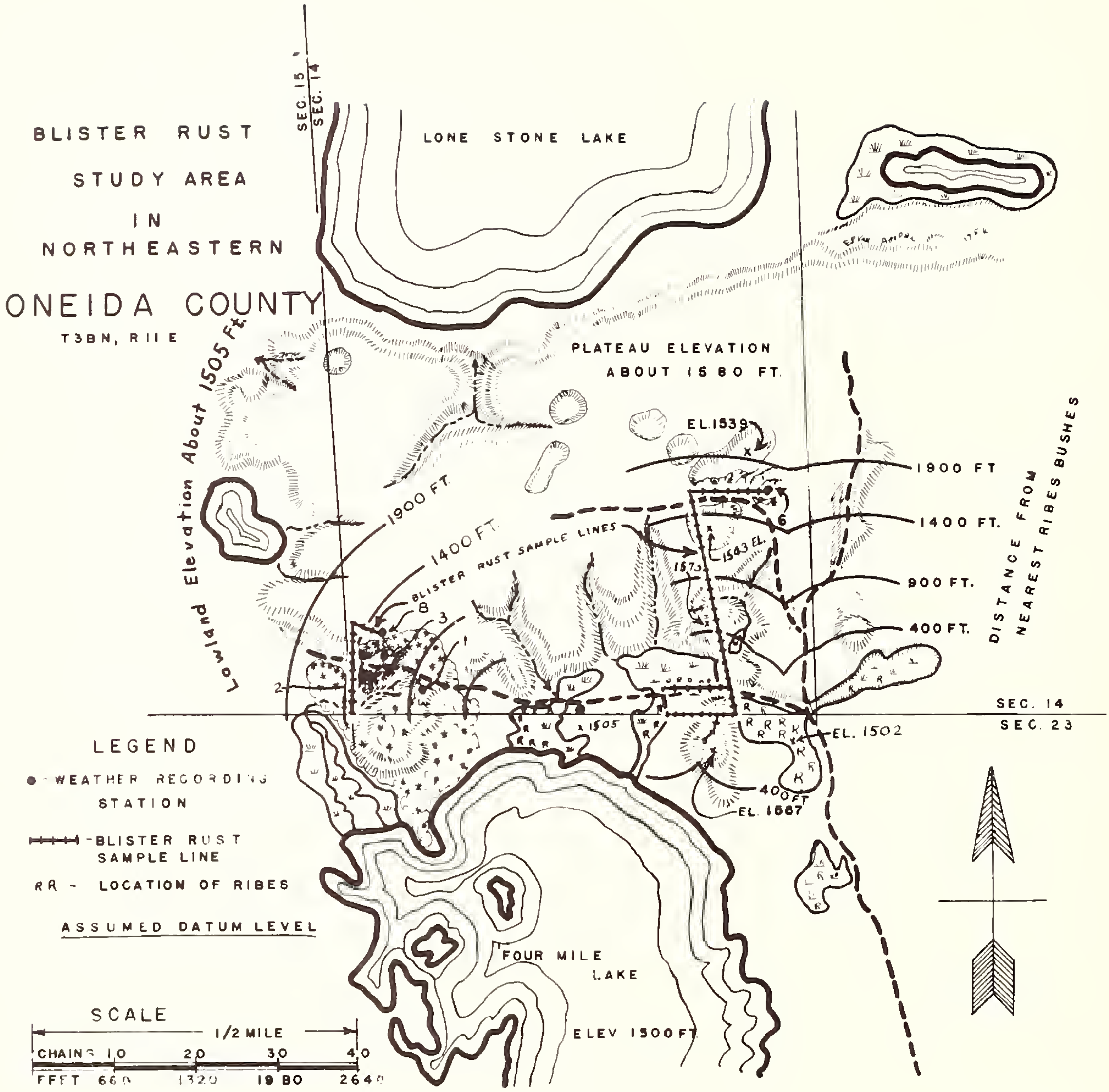

Figure 6.--Map of blister rust study area in Oneida County in northeastern Wisconsin (Oneida-5, fig. 1).

In seven other areas blister rust distribution on white pine was observed without regular samples being made. In these areas the type of stand, topography, ribes abundance, and an estimated percentage of trees with blister rust were recorded.

To correlate microclimate with the incidence of blister rust, temperature and humidity distributions were studied in the six areas circled in figure 1. These included the five intensively sampled areas described above plus an area in Dane County. Two of the southern areas (Iowa-1 and Sauk-1) and one of the northern areas (Oneida-5) were hilly. The other three (Dane-1, Rock-1, and Forest-3) were level to gently rolling. Detailed temperature and humidity studies were made in the Rock County area and profiles drawn. In all of the six areas, three

to nine hygrothermographs or electric recording thermostats (recording the length of time under 68° F.) were used to show the simultaneous course of weather on different sites within a given area.

Subsequent studies of rust incidence were made in 1954 to check the site value rust index which was first presented in the spring of 1954 (Van Arsdel 1954). Among these was another intensively studied area in Grant County containing 31 plots where site indices from aerial photographs were correlated with rust incidence on pine. Blister rust distribution was also sampled extensively in 30 areas along the western border of the State. As in other sample areas, infection on trees was recorded.

Blister rust distribution

In the Rock County area the infected trees were concentrated in certain locations as indicated by solid black triangles in figure 3. The map was prepared from aerial photographs, and openings in the crown canopy were shown. Of the 425 trees, 6 percent were infected with blister rust. Infected trees had from 1 to 11 cankers per tree. On the 28 infected trees, 52 cankers were present. Infected trees were concentrated in small openings in the woods (diameter of opening related to the surrounding tree heights was about 0.5) and in kettle holes. The infection occurred in wave years such as 1941, 1944, and 1947 without additional spread throughout the stand.

In Iowa-1 (fig. 4) the small, north-facing valley contained all of the rust found in sampling the area except in four isolated cases: Two on the northeast slopes and two on a southwest slope in another nearby valley. The height distribution of the cankers in the valley was notable; 75 of the 85 cankers in the 108 plots were less than 2 feet above the ground; the other 10 cankers were 2 to 4 feet above the ground. Blister rust infection in this valley failed to conform to the normal wave years found in other areas. Apparently, then, purely local conditions were dominant. When the rust presence on sample plots in Iowa-1 was combined with other Iowa and Sauk County areas and compared with other areas in a tabulation for the State, rust was found to be most commonly present in sheltered valleys, on moderate slopes (3 to 20 percent), at the bases of hills, and in small openings in the crown canopy.

The distribution of blister rust in the canyon in Sauk County (profile diagram in fig. 5) was confined to the lower slopes and the bottom. It was most prevalent in openings. All of the 19 cankers found were less than 6 feet from the ground--12 of them were less than 2 feet from the ground.

The incidence of blister rust on 446 plots in 50 areas distributed throughout the State is summarized in table 1 by site, classified in 5 different ways. To clarify the site descriptions, the various classes of aspect, slope, and position on hill are diagrammed in figure 7.

The data in table 1, also separated into three geographical areas, show the presence of rust increasing as one moves from south to north. In the southern and lowland western counties the rust was strongly affected by site. In the west central upland (a 1200- to 1300-foot-high plateau) less site influence was shown. In the northern part of the State rust intensities were generally high, with a good probability of rust occurring on any site; however, a certain amount

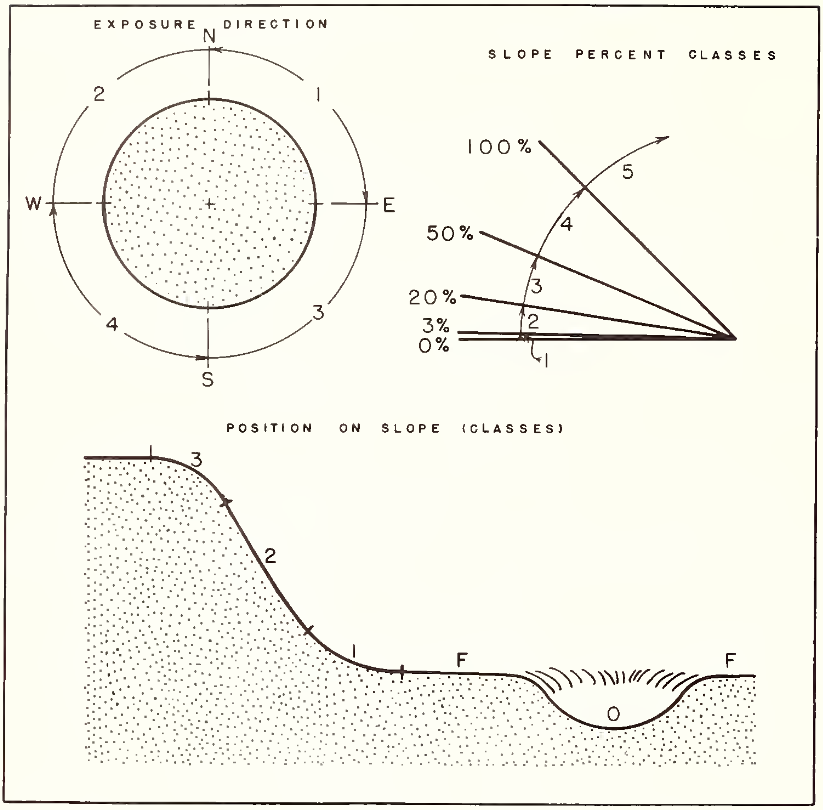

Figure 7.--Site classes used in classifying and defining blister rust infection data. Numbers (and F) are the codes for the various positions.

of site influence was noticed. In the north occurrence of rust was not always favored by the same sites as in the south, but in all areas less rust was found on pines under an overstory. Other tests, such as the average number of cankers per tree, showed localization in the northern part of the State, although nearly all samples had rust present.

By way of summary, from Wood County south the rust was localized at the bases of slopes, on moderate slopes, in kettle holes (found in Rock County which does not appear in table 1 because no standard plots were established there), and in small openings. Direction of slope was not important. A similar local distribution was found from Barron County south in the lowlands of western Wisconsin. In southwestern Wisconsin, high ground had more general rust. In northern Wisconsin, from Marathon County north, between 68 and 100 percent of all plots on a site had rust present.

The rust distribution according to site and distance from the nearest ribes bushes for Oneida-5 (fig. 6) is presented in table 2. Weber[1/] found infection three-fourths of a mile from the nearest ribes bushes. In the Oneida area infection occurred on from 6 to 9 percent of the trees growing 1400 to 1900 feet from the nearest ribes. This demonstrated that under favorable conditions blister rust could spread for considerable distances from a few scattered ribes bushes.

1/ Weber, Ray. Unpublished blister rust control survey data. Antigo, Wis., Blister Rust Control Office, Forest Service, U.S. Dept. of Agric.

Table 1.--Blister rust presence on white pine in 0.01-acre plots according to site

Site description and code[1]		Southern and lowland western Wisconsin[2]: Plots in site class	Southern and lowland western Wisconsin[2]: Plots with rust present	West central upland[3]: Plots in site class	West central upland[3]: Plots with rust present	Northern Wisconsin[4]: Plots in site class	Northern Wisconsin[4]: Plots with rust present
		Number	Percent	Number	Percent	Number	Percent
Aspect							
NE	(1)	102	23	8	75	27	89
NW	(2)	91	23	5	80	28	96
SE	(3)	21	33	7	71	24	62
SW	(4)	58	26	11	45	32	88
Flat	(F)	12	8	0	--	20	90
Slope							
0-3%	(1)	34	18	0	--	31	90
3-20%	(2)	50	42	9	56	58	86
20-50%	(3)	98	33	10	60	38	87
50-100%	(4)	65	11	12	75	4	100
Over 100%	(5)	37	3	0	--	0	--
Position on hill							
Kettle hole	(0)	0	--	0	--	2	100
Base	(1)	56	54	2	100	27	93
Slope	(2)	153	22	25	60	61	79
Shoulder	(3)	64	5	4	70	29	93
Flat	(F)	11	9	0	--	12	83
Special position							
In valley		50	64	4	100	7	100
Not in valley		234	15	27	59	124	85
Vegetation							
Small opening	(1S)[5]	56	39	4	100	13	85
Large opening	(1L)[5]	13	8	2	100	5	80
Brush	(2)	37	27	3	100	68	90
Grass	(3)	20	20	13	54	23	91
Tree covered	(4)	158	19	9	44	22	68
All plots		284	24	31	65	131	86

1/ Aspect, slope, and position on hill are more exactly defined in figure 7 according to code numbers.

2/ Based on 2,006 trees in 28 areas in Adams, southern Barron, Buffalo, Dane, Dunn, Eau Claire, Grant, Iowa, lowland La Crosse, Richland, Sauk, lowland Vernon, and lowland Wood Counties.

3/ Based on 366 trees in 5 areas in upland La Crosse and Clark Counties.

4/ Based on 889 trees in 17 areas in Ashland, northern Barron, Bayfield, Douglas, Forest, Marathon, Oneida, and Washburn Counties.

5/ A small opening has a D/H ratio of from 0.25 to 1.00; large has a ratio of 1.00 or greater.

Table 2.--Blister rust distribution in a white pine reproduction area in northeast Oneida County (Oneida-5). Fifty to 100 feet of living stem of Ribes glandulosum per acre were present on one side of the area

Distance from light ribes concentrations (feet)	Position of plot on hills 1/	Plots	All trees	Trees infected	Cankers per tree
		Number	Number	Percent	Number
0-400	F	0	0	--	--
	1	7	37	32	0.57
	2	7	54	26	2.78
	3	5	27	7	.07
400-900	F	1	10	0	0
	1	1	20	35	.35
	2	4	30	7	.07
	3	1	10	10	.10
900-1400	F	1	12	8	.08
	1	2	22	18	.23
	2	3	72	7	.07
	3	6	71	3	.03
1400-1900	F	2	32	9	.09
	1	4	36	6	.06
	2	8	128	9	.09
	3	5	34	6	.06
Basis		57	595		

1/ See figure 7. Position codes are: F = flat, 1 = base, 2 = slope, 3 = shoulder.

The distribution of rust cankers for the year's growth on which they were initiated was compared for two northern Wisconsin areas within 5 miles of each other. The cankers on Forest-3 were almost evenly distributed through the years except for 1951 when infection was heavier. This area had very heavy pine infection; almost all of the trees had cankers. About 100 feet of live stem per acre of Ribes glandulosum and R. triste were scattered throughout the area. Apparently conditions were favorable for the spread of rust every year. Oneida-5 was mostly far from ribes bushes, and much of the pine was on an elevated plateau. In this area infection was more concentrated in wave years than in Forest County, although some occurred almost every year. The biggest wave year in the Forest-3 area was on 1951 growth; that in the Oneida-5 area was on 1950 growth. Thus, rust infection was in small waves or general every year in northern Wisconsin depending on the site; the wave years were not always the same, nor were they necessarily the same as those for southern Wisconsin.

The height of cankers above the ground also was recorded for the two areas. Trees ranged from seedling-size to 100 feet in height. Forest-3 had 251 cankers less than 2 feet from the ground, 56 from 2 to 4 feet, 23 from 4 to 6 feet, and 8 cankers more than 6 feet above the ground. Of 13 cankers for which height was recorded on Oneida-5, 9 were less than 2 feet above the ground and 4 were 2 to 4 feet. Honey (1942) reported that in Brown County (eastern H plot in fig. 1) 98 percent of 307 cankers were within 6 feet and all cankers were within 10 feet of the ground. These results suggested that rust infection was dependent on moisture near the ground. Cankers occurred higher in Forest-3, a favorable area, than in Oneida-5. A preponderance of the blister rust infection in all of Wisconsin took place near the ground, but in the northern part of the State occasional cankers higher in the trees were observed.

To study the relation of blister rust incidence to the size of forest openings, data on plots falling in openings in the crown canopy from all of southern and lowland western Wisconsin (the part of the State where rust was confined to locally cool moist places) were analyzed. The size of a forest opening was designated by the ratio of the diameter of the opening to the height of the trees around it. This was called the diameter/height or D/H ratio (Geiger 1950). The average number of cankers per tree was graphed in relation to the D/H ratio for the 57 plots that fell in openings surveyed in the microclimatic distribution areas (column 1, table 1). The diameter-height ratio of the forest opening was shown to have an effect on blister rust incidence.

A chi-square test showed the favoring effect of a small opening (D/H ratio less than 1.0) over that of a large opening (D/H more than 1.0) to be significant at the 3-percent level. When the average number of cankers per tree is graphed over the diameter of openings expressed as multiples of the height of the surrounding trees, it appears that a D/H ratio of 0.5 is most favorable to rust. Additional samples are needed, however, before definite conclusions can be drawn. Other test groupings of the same data, such as percent presence in openings by diameter classes, seem to indicate the same optimum size of opening. Rust was rare in openings with a D/H of less than 0.25 and very rare where the D/H was more than 1.0.

Temperature and moisture

The general relation of climate and weather to blister rust infection and prevalence was pointed out in the introduction. Before rust infection could be correlated with microclimatic conditions, more exact information was needed on the local distribution of temperature and moisture. Since it had been noted that rust occurred more frequently in kettle holes and in openings in the forest, these were chosen for study. To get broad representation, data were also collected on hilly sites and in some other situations. A special study was made of the effects of certain vegetative covers.

In a Kettle Hole

To determine the temperature and moisture in a gently rolling forested area, detailed studies were made in Rock-1. Sample readings were made at different times in the evening and at night on several occasions with a platinum resistance thermometer and lithium chloride dew-point indicator.

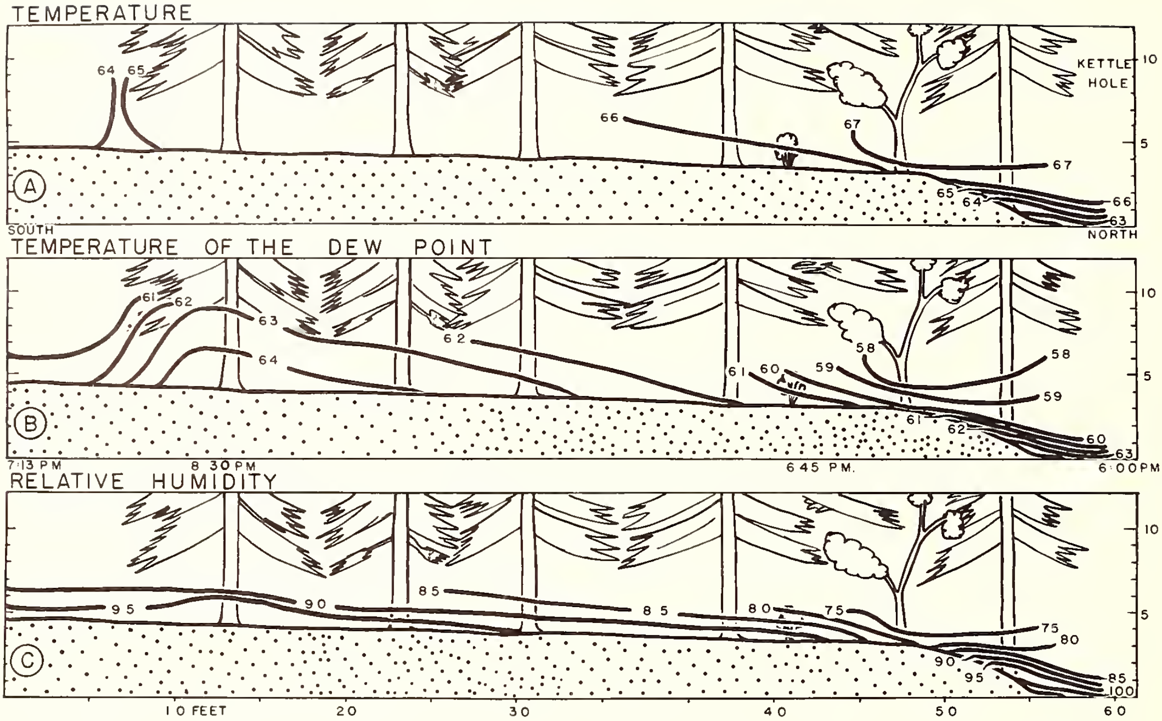

Figure 8.--Profile of temperature (degrees Fahrenheit) and moisture at the edge of a kettle hole in Rock County. Measurements were made from 6:00 to 8:30 p.m. July 12, 1951 (sunset 7:40 p.m.). Vertical and horizontal scales are in feet.

Temperature and humidity profiles for a slope at the edge of a kettle hole are shown in figure 8. From 6:00 to 6:45 p.m. on July 12, 1951, the temperature was lower near the ground (fig. 8A). If the amount of moisture had been constant at all heights above the ground, then the relative humidity would have been higher near the ground because of the lessened moisture-holding capacity of the cooler air. However, the amount of moisture in the air indicated by the temperature of the dew point was greater near the ground. Thus, the combination of lower air temperatures and more moisture resulted in a much higher relative humidity than existed 3 feet above the ground.

The shoulder of the slope was both warmer and had less moisture, indicated by a lower dew point, than the kettle hole or the ground away from the shoulder. Cold air drainage towards the swamp could be felt by hand, and the better drained, drier soil of the shoulder contributed less moisture to the adjacent air. Moist air layers near the ground in the kettle hole were apparently common, as a ribes bush had moderate rust infection up to 12 inches above the ground while the upper part of the bush was free of rust. Compared with the surrounding higher ground, a kettle hole was cooler and had a higher relative humidity.

These measurements are in accord with other observations that the moisture source of locally high relative humidities was the soil: Air over irrigated desert soil had only localized increases in relative humidities (Ohman and

Pratt 1956); air immediately above irrigated rice paddies contained more moisture than air above levees separating paddies;[2/] and the assertion by Geiger (1950, p. 90) that in the air layer near the ground the high relative humidity always comes from the ground.

In an Opening in the Forest

Temperature profiles were made of an opening in an oak forest (D/H = 0.50), of an adjacent wooded site, and of an open field site in Rock County. The opening was at location 5B in figure 3 (page 6). Details of the forest opening are mapped in figure 9. The hygrothermograph shelter at Station 1 was located in this opening. Station 2 was in the woods 91 feet west; Station 3 was 855 feet west in an open plantation of 3-foot red pine (fig. 10).

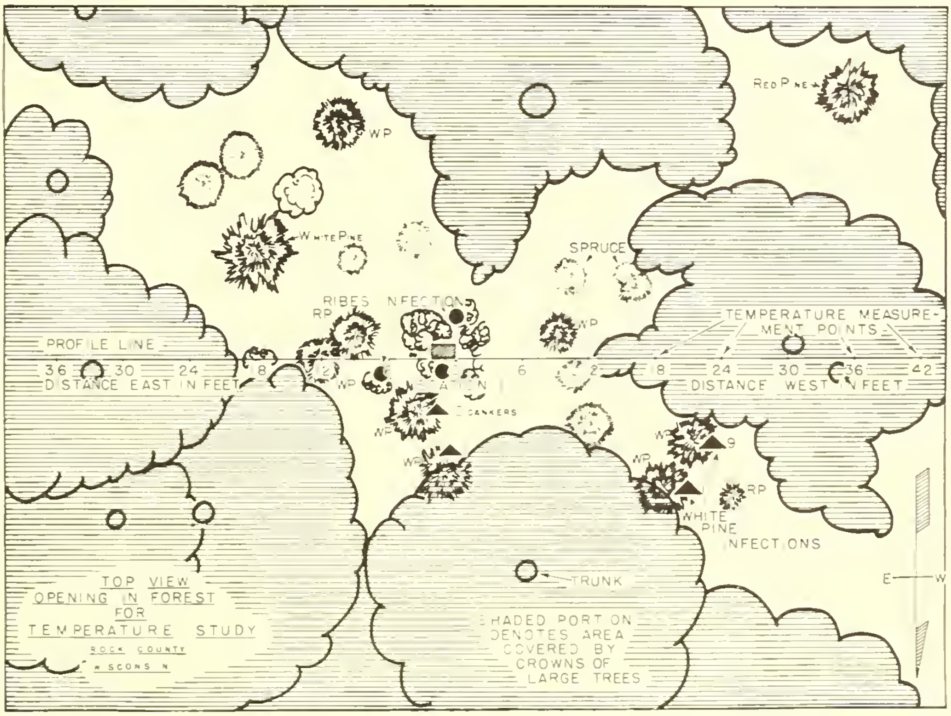

Figure 9.--Map of an opening in the forest in Rock County-1 at weather station 1. D/H is 0.50.

Observations of the temperature and humidity were made on various evenings. On August 31, 1951, the measurements were made from 7:48 p.m. to 8:40 p.m. (sunset at 6:35 p.m.) during a drizzle, and the temperatures at the sites of the three shelters (fig. 10) differed by less than 1° F. A nearby kettle hole about 30

2/ Van Arsdel, E. P., J. D. Panzer, E. C. Tullis, V. E. Green, Jr., and R. D. Schein. Microclimatic variations in a Florida rice paddy. Unpublished manuscript in files of University of Wisconsin.

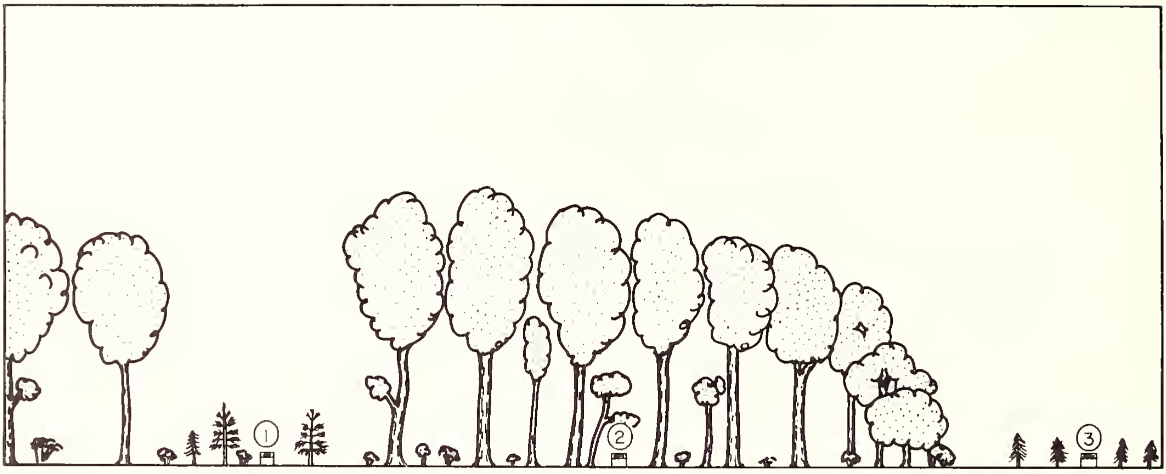

Figure 10.--Diagrammatic profile showing locations of three weather stations: 1, in small opening; 2, in woods; 3, in open plantation.

feet deep was about 3° F. cooler at the bottom. Thus, on a cloudy, drizzly night there was little local variation in temperature.

On a clear night with a light breeze (September 6, 10:00 p.m. to midnight) air temperature differences were greater. At 18 inches above the ground the temperature in the opening was 57.0° F. (Station 1), at Station 2 it was 58.7° F., and at Station 3 it was 54.9° F. Inversions were not present, as cooler air was transported over warmer soil. Under a tree cover temperatures diminished slightly with increased height.

On a clear, still night (September 7-8) horizontal temperature differences were still greater, and inverted temperature profiles were noted. At 18 inches above the ground the temperature difference was 4.1° F. between the wooded station and the cooler one in the open.

In summary, these studies around the opening, where blister rust was most prevalent, and in varied vegetation cover showed the greatest differences in temperature in calm, clear weather; smaller differences on windy nights; and practically no difference on cloudy, rainy nights. The open area was coldest at night, the woods the warmest, and the opening intermediate.

Although the measurements show basic differences that must be known for microclimatic studies, they give no real insight into just what limits the natural spread of blister rust. To extend the scope of measurements, hygrothermographs were used to find average conditions in these same areas in Rock-1 at the same weather stations. The hygrothermographs were placed in shelters and operated from August 11 to November 1, 1951.

These instruments had bourdon tube elements for recording temperature and hair elements for humidity. The measuring elements were about 21 inches above the ground. All shelters were constructed with the floor 18 inches above the ground, about the same level as the ribes foliage in the area and the average level for the rust cankers found on the areas surveyed at that time. The temperature inside the boxes varied only about 0.4° F. from the temperature outside during

the times of most rapid diurnal temperature change. Synchronized thermometers were kept in the shelters at all times, and weekly humidity checks were made with a sling psychrometer.

The averages of temperatures recorded showed that the open plantation at Station 3 was warmest in the day and coolest at night. Station 2, under the crown cover, was the warmest at night and the coolest by day. The opening in the woods (Station 1) was intermediate in its temperature extremes, but it was under 68° F. for about 3 hours more per day than either of the other stations. The other two stations had equal daily periods of cool temperature. Thus, the opening in the forest (D/H = 0.50) had a longer period of coolness than either of the other stations; yet its nightly minimum was not as cool as in the open.

The modifying effect of a small opening also included a delaying action on frost. On September 23, 1951, the hygrothermograph in the open at Station 3 recorded 32° F., and weeds in the sodded, colder kettle holes were killed. Station 1 in the small opening had a low of 38° F. that night. On September 25 the temperature dropped to 25° in the open, whereas the small opening had a minimum of 33°. The opening recorded 31° on October 10, 1951, and finally had a killing frost on October 28, when the temperature dropped to 28°. This 33-day delay of frost in the opening could permit infected ribes leaves to survive longer in the autumn.

To observe the effects of the small opening on maximum high temperatures, the daily maxima were inspected. During the period that these records were kept, the hottest days were August 11 and 29. The open field had maxima of 89° and 88° respectively on these two dates. The woods had maxima of 79° and 82°, and the opening had maxima of 77° and 80°. Thus, the high temperatures damaging to rust occurred in the open field but not in the small opening in the woods.

On a Hilly Site

To study the effects of rough topography and its vegetation on the temperature and relative humidity, nine weather stations were established on a variety of sites in Iowa-1 (fig. 1, page 4). A map of this area appears in figure 4 (page 7) and a diagram of the valley in figure 11. The instruments, their locations, time of operation, cover conditions, and sites are described in table 3.

Figure 11.--Diagram of the small valley in Iowa-1 showing weather station locations.

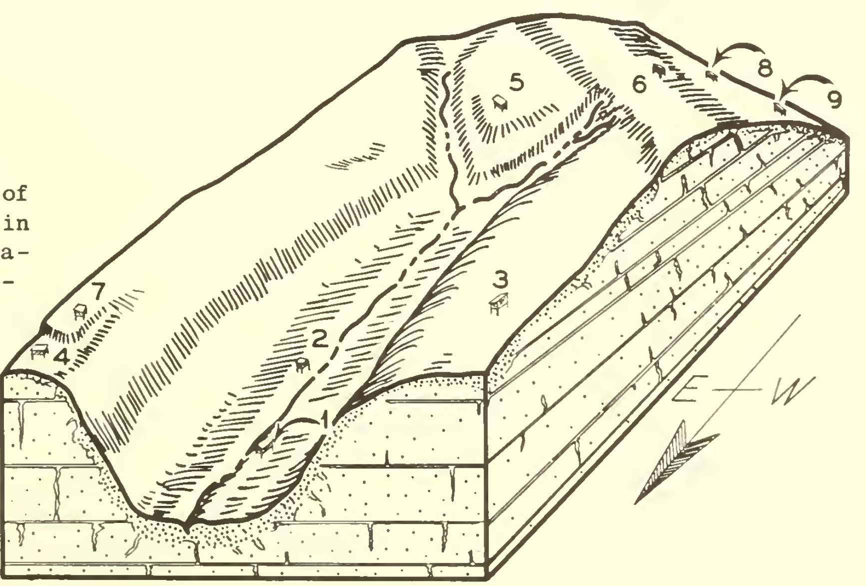

Table 3.--Description of weather instrument sites in Iowa-1

Station	Instrument	Time of operation	Cover condition	Exposure 1/	Slope 1/	Position on slope 1/
1	Hygro-thermograph	July 1 - Aug. 25	Heavy crown cover of a 70-foot white oak (in valley)	2	2	1
2	Hygro-thermograph	July 1 - Aug. 25	Small opening (D/H = 0.50) (in valley)	1	2	1
3	Thermograph	July 1 - Aug. 17	100-foot white pines with an understory of oak	1	4	3
4	Hygro-thermograph	July 1 - Aug. 25	Exposed ridge surrounded by scattered trees	2	2	3
5	Hygro-thermograph	July 8 - Aug. 17	70-foot white oaks	1	3	2
6	Hygro-thermograph	July 8 - Aug. 25	Recently pastured open field (on flat ridge)	2	2	2
7	Battery-operated recorder 2/	Aug. 18-25	Open-grown, broad white pine tree	4	1	3
8	Hygro-thermograph	Aug. 18-25	Small opening (D/H = 0.50)	4	3	2
9	Thermograph	Aug. 18-25	50-foot white oaks	4	3	2

1/ See diagram in figure 7 (page 10) for explanation of codes.
2/ This measured the time under 68° F. when a thermostat switched on a timer.

The average temperatures and hours per day under 68° F. for the nine sites and for the official Madison (Truax Field) Station are shown in table 4. Not all the instruments were working at all times, and complete records are not available. However, the data on each line of the table may be compared safely, since the averages were based on records for exactly the same days. For example, the average maximum temperature of 74.6° at Station 1 and 81.2° at Station 4 were computed from records for the same 47 days between July 1 and August 24.

The differences in temperatures between the different sites increased as the days became shorter and the angle of the sun decreased. In the 10 days from July 12 to 21 the average daily maximum at Station 1 (oak-covered, in valley)

Table 4.--Averages of specified temperature records and of hours per day under 68° F., Iowa County-1, for various periods, 1952

Period averaged	Type of record	Weather observation stations (from fig. 11)						
		1	2	3	4	5	6	Madison (Truax)
47 days between July 1 and Aug. 24	Maximum °F.	74.6	75.8	--	81.2	--	--	86.7
	Minimum °F.	59.2	59.5	--	57.1	--	--	64.0
	Hours/day under 68° F.	14.5	13.8	--	12.5	--	--	9.7
43 days between July 1 and Aug. 17	Maximum °F.	--	77.3	75.5	85.9	--	--	84.7
	Minimum °F.	--	60.0	59.2	61.3	--	--	66.0
	Hours/day under 68° F.	--	12.6	12.0	12.5	--	--	8.4
31 days between July 8 and Aug. 17	Maximum °F.	--	76.7	--	82.1	77.8	83.0	82.2
	Minimum °F.	--	60.8	--	58.5	61.9	59.1	63.4
	Hours/day under 68° F.	--	12.6	--	11.7	12.9	11.0	7.6
10 days from July 12 to July 21	Maximum °F.	79.5	80.7	79.8	86.2	82.1	85.6	84.3
	Minimum °F.	66.3	65.8	65.8	65.5	67.9	64.4	69.2
	Hours/day under 68° F.	5.2	6.4	4.7	6.3	3.7	6.8	3.6
10 days from Aug. 8 to Aug. 17	Maximum °F.	72.2	73.2	72.5	79.7	74.8	82.0	80.2
	Minimum °F.	57.2	58.8	56.2	56.1	59.1	57.4	60.0
	Hours/day under 68° F.	19.2	16.2	17.2	14.7	14.4	13.5	10.2
6 days from[1/] Aug. 19 to Aug. 24	Maximum °F.	69.0	70.5	--	76.7	--	77.8	74.7
	Minimum °F.	53.0	53.5	--	52.3	--	52.2	54.0
	Hours/day under 68° F.	21.2	18.6	--	14.0	--	14.5	14.8
Extremes for period July 1-Aug. 25	Highest °F.	86	88	87	96	91	96	94
	Lowest °F.	44	44	46	41	48	42	44
	Hours/day under 68° F.	24	24	24	24	24	18	20
	Days under 68° F.	5	4	4	1	1	0	0

1/ The only weather records averageable for Stations 7, 8, and 9 are for the 6 days from Aug. 19 to 24. Data are as follows:

	7	8	9
Maximum °F.	--	73.5	77.3
Minimum °F.	--	54.2	54.3
Hours/day under 68° F.	16.6	15.5	14.3

was 4.8° cooler than at the Madison Truax Station. In the 10 days from August 8 to 17 it averaged 8.0° cooler--almost twice the difference. Other sites showed comparable differences between early and late summer.

Some late-summer data from table 4 for several of the stations are presented as percentages to show the magnitude of local variation encountered. For the 10 days from August 8 to 17, Station 1 (oak-covered, in valley) was cool longest; it was under 68° F. 88 percent longer each day than was the official Madison temperature. Other stations in order of descending length of time under 68° for this 10-day period were as follows: Station 3 (pine-covered, northeast slope), cool 69 percent longer than at Madison; Station 2 (in opening in valley), cool 59 percent longer; Station 4 (1.0 opening, on ridge), cool 44 percent longer; Station 5 (oak-covered, north slope), cool 41 percent longer; and Station 6 (open field, wide ridge), cool 32 percent longer each day.

In summary, while weather variations caused some differences between the sites under general late-summer conditions, high temperatures by day were in general warmest in the large opening, in the open field, and on the covered southwest slope. It was not quite so warm in the opening on the southwest slope or at Madison, and it was coolest during the day in the narrow valley and on north and east slopes. The sites that were coolest for the longest periods were in the valley; two on pine-covered shoulders of the valley were cool fairly long, and more exposed sites were cool for shorter periods. The sites with the lowest temperatures at night were those most openly exposed to the sky. Those located where cool air could drain into them, even though they were not exposed to the sky, were of moderate low night temperature; and those sites covered by broadleaf tree crowns and up on the southwest slope were warmest.

Humidity data (obtained with hair hygrometers) from the same stations were examined to determine which sites had saturated air (100-percent relative humidity) for the longest periods of time with the following results:

Station	Number of hours per day at 100-percent humidity 1/	
	Aug. 8-17	Aug. 19-24
1--Oak-covered, in valley	17.4	17.7
2--Small opening in valley	22.4	20.2
4--1.0 opening on ridge	16.3	16.2
5--Oak-covered, north slope	17.0	--
6--Open field, wide ridge	13.5	13.3
8--In small opening on southwest slope	--	15.2

1/ At Madison the highest relative humidity recorded during Aug. 8-17 was 98 percent; during Aug. 19-24 it was 95 percent.

In the 10 days of August 8 to 17 the air was saturated 66 percent longer in the small opening in the valley (Station 2) than in the open field on the ridge (Station 6). For both periods of measurement the small opening in the valley also had saturated air longer than under the crown cover in the valley (Station 1). It was cool longer under the crowns than in the small opening. A small

opening on the southwest slope (Station 8) was moist almost as long as the large opening on the north slope (Station 4) and 2 hours more per day than in the open field (Station 6). The stations in the small openings were moist considerably longer than those in the open or under trees on the same type of site. Station 1 on the valley floor averaged 100-percent relative humidity only slightly longer per day than Station 5 on a convex slope under the same type of crown cover. This indicated that the length of time the air was saturated was strongly influenced by vegetation even in rough topography of this sort, and that small openings in the forest had saturated air more of the time.

In Some Other Situations

Other areas were studied to see if the temperature and moisture distribution were similar to those found in Rock and Iowa Counties. In Sauk-1 (fig. 1, page 4) hygrothermographs were operated from October 27 to November 10, 1952, an extremely windy and dry period which offered reduced chances for local weather variation. The four sites are indicated by sketched shelters and numbers in figure 5, page 7). Station 1 was near the shoulder of the southwest-facing slope on the northeast wall of the canyon. It was covèred by a 15-foot white pine. Station 2 was on the floor of the canyon in brush that offered broken cover (with the shelter open to the sky). Station 3, under an overhang at the shoulder of the southwest wall of the canyon, was under 30-foot white pines; it was open to the northeast of the shelter. Station 4 was on a rock promontory near the bottom of the canyon under a thick cover of 15- to 30-foot white pines. The maximum and minimum temperatures and relative humidities are given in table 5. These measurements showed that, even in windy weather when there was considerable mixing of the air, the narrow, deep canyon exerted a great influence on the local climate so that it was cooler and more moist at night in the bottom of the canyon than on the shoulders.

Table 5.--Averages and extremes for specified temperature and relative humidity records, Sauk County-1, Oct. 27 to Nov. 10, 1952

Station and site	Minimum temperature		Maximum temperature		Maximum relative humidity	
	Average	Extreme	Average	Extreme	Average	Extreme
	Degrees F.		Degrees F.		Percent	
1--N. E. Shoulder	35.1	24	53.0	68	55.8	86
2--Bottom of canyon	29.2	16	50.2	66	75.4	1/100
3--S. W. shoulder	39.5	26	51.9	64	58.5	80
4--Under pine on point in canyon	32.4	19	49.7	64	72.0	2/100

1/ During one 4-hour period.
2/ During one 16-hour period.

In Oneida-5 and Forest 3 hygrothermographs were operated in six locations on each area in August, September, and October of 1953. The results showed that temperature and moisture distributions were modified by site in the same manner in northern Wisconsin as in the southern part. Some results in Oneida-5 are indicated in table 6.

Table 6.--Averages for specified temperature records and for hours per day under 68° F., Oneida County-5, Sept. 15-21, 1953

Site	Temperature (°F.) Average minimum	Temperature (°F.) Average maximum	Hours per day under 68° F.
Exposed on hill	43.4	67.0	21.7
In opening, D/H = 0.50	43.2	59.1	24.0

Under Various Vegetative Covers

Studies made at Madison (Dane-1, fig. 1) in 1951-54 gave some insight into vegetative effects on local climatic variations. The area was an experimental planting of pines, hybrid poplars, and ribes bushes about 1 mile from the Madison City Office of the U.S. Weather Bureau. Soon after the study period began a large hospital was built near the area, causing conspicuous changes in site. The earth-moving in 1951 piled up a large hill next to the area and changed it from the top of a gentle hill (1- to 3-percent slopes) to the base of a steep slope. The vegetation present acted as cold-air dams on a slope and made cool places in the area. By 1953 erosion had filled in the stand with a fresh layer of dirt about 2 feet deep on the south side and 6 inches deep on the north edge of the stand. The ground then had a 3-percent slope with a north aspect. In 1954 weeds had appeared and pine needles once again covered the ground. One notable effect of the site change was that while the site had had a rust-free history prior to the earth-moving, in 1954 blister rust was found on 1951 wood of white pine.

The periods of saturated air recorded on a hair hygrometer 18 inches above the ground (during summers 1951-54) did not correlate with the periods of high humidity at the Madison City Office of the Weather Bureau but rather with the periods of well-distributed rainfall when the soil was moist. Light rains on dry soil were not sufficient to give saturated air. The City Office, then on the top floor of a 75-foot building on a high hill, records the air-mass humidity. The air was almost never saturated at that elevation.

Two 10-day averages indicative of the 1952 results are presented in table 7. The sites were (1) open to the sky in 2-foot ribes bushes, and (2) under aspen (*Populus* spp.) crowns. The aspens were about 20 feet high, with the lowest limbs 6 feet above the ground. The September data showed greater extremes of temperature in the open and a reduced humidity under the crowns of trees at night when dew formed on the top radiating surface--the top of the leaf canopy. The October differences are less noticeable because of defoliation of the aspen.

Hygrothermographs, operated on 8 sites 18 inches above the ground in this small area during much of the summer of 1954, gave some indications of effects of different types of vegetation on a fairly uniform topography. Table 8 describes the sites and gives temperature and humidity averages for the 13-day period

Table 7.--Averages for specified temperature records, for hours per day under 68° F., and for hours per day with saturated air, during two periods, Dane County-1, 1952

Date	Station and site	Temperature (°F.)		Average hours under 68° F.	Average hours with saturated air
		Average minimum	Average maximum		
Sept. 6-16	1--In open brush	57.0	82.9	13.4	9.7
	2--Aspen covered	58.1	75.9	14.8	.6
Oct. 15-24	1--In open brush	31.6	57.7	23.5	.8
	2--Aspen covered 1/	35.4	55.4	23.6	1.5

1/ Defoliated.

July 18-30. The sites in order of increasing minimum night temperatures were: In open grass 12 feet north of the stand, at exposed edges, the somewhat warmer 1.0 opening in the pine, under light aspen (trees partially killed by soil washed from higher bare ground), among ribes bushes, under pine, and the warmest was under heavy poplar crowns. The daily maxima were not exactly in the reverse order, but approached it; the ribes brush site was warmest by day, the open grass was next, and the dense pine and dense poplar were the coolest. The air was drier under the vegetation. The driest sites (based on the average daily lowest relative humidities) were under the poplar, next driest was under the pines. The site under the heavy poplar had saturated air for the shortest period each night; under the pine the air was also saturated for a relatively short period.

In two of the locations (Stations 1 and 8) hygrothermographs were also placed at elevations of 4 inches and 72 inches above the ground. Results for these and the 18-inch elevations during the 13-day period (September 5-17, 1954) are shown in table 9; also shown are data from Stations 6 and 7 at 18 inches above ground. Low night temperatures were cooler above the ribes bushes than in the leaf layer (18 inches) or under the bushes, but the air was saturated longest near the soil. Under the aspen and under the pine a shorter period of air saturation occurred at the 18-inch level. At the 6-foot level under the aspen the air averaged driest and the rare saturation periods were short. This reemphasizes the dryness under tree canopies and the greater dryness as elevation from the soil is increased.

Table 8.--Averages and extremes for specified temperature and relative humidity records, for hours per day under 68° F., and for hours per day of saturated air, Dane County-1, July 18-30, 1954 (instruments 18 inches above ground)

Station and site	Temperature				Under 68° F.		Minimum relative humidity		Saturated air	
	Minimum		Maximum							
	Average	Extreme	Average	Extreme	Average	Shortest time	Average	Extreme	Average	Shortest time
	°F.	°F.	°F.	°F.	Hrs.	Hrs.	Percent	Percent	Hrs.	Hrs.
1--Ribes brush 2 feet high	64.4	59	87.4	93	7.2	1/ 0	57.6	46	13.7	9
2--Under light aspen	63.9	58	84.4	90	7.8	2/ 0	49.5	38	11.1	3
3--Open grass 12 feet north of grove	59.8	54	86.6	92	11.1	3/ 0	--	--	--	--
4--Opening in pine, D/H = 1.0	63.7	58	86.2	91	8.0	1	54.4	37	9.2	1
5--Edge of grove, S. W. corner	61.5	54	86.5	92	10.2	2	--	--	--	--
6--South edge grove at slope base	62.5	56	84.0	88	9.6	2	54.8	37	14.0	4
7--Under pine (duff cover)	64.6	59	79.8	87	7.0	3/ 0	53.3	42	7.4	4/ 0
8--Under heavy poplar	65.0	60	79.8	85	5.7	2	51.5	33	3.5	4/ 0
Truax Field--flat land; station on top of 25-foot building	61.7	56	88.0	93	6.1	1	43.7	31	0	5/ 0
City--station on top of 75-foot building on hilltop	65.5	60	83.3	88	--	--	--	--	--	--

1/ Never under 68° F. for 3 days.
2/ Never under 68° F. for 2 days.
3/ Never under 68° F. for 1 day.
4/ Air never saturated for 1 day.
5/ Air never saturated for 13 days.

Table 9.--Averages and extremes for specified temperature and relative humidity records, for hours per day under 68° F., and for hours per day of saturated air, Dane County-1, Sept. 5-17, 1954 (instruments at three different heights above ground

Station and site	Elevation above ground	Temperature				Under 68° F.		Minimum relative humidity		Saturated air	
		Minimum		Maximum							
		Average	Extreme	Average	Extreme	Average	Shortest time	Average	Extreme	Average	Shortest time
	Inches	°F.	°F.	°F.	°F.	Hrs.	Hrs.	Percent	Percent	Hrs.	Hrs.
1--2-foot brush	4	54.1	47	67.7	91	22.0	9	78.9	61	18.5	10
	18	56.9	52	72.5	97	19.0	6	67.6	33	17.1	10
	72	52.8	45	70.2	93	20.0	9	70.2	35	17.9	5
6--South edge of grove	18	51.0	42	77.4	91	20.8	10	74.1	50	20.4	9
7--Under pine	18	56.8	49	82.3	90	20.8	7	73.0	30	14.9	2
8--Under aspen	4	57.0	51	65.3	90	19.8	4	66.9	33	12.7	6
	18	56.3	49	69.4	94	19.7	7	65.8	32	14.1	7
	72	57.0	50	70.4	94	18.8	3	63.3	33	9.2	0
Official-- Madison Truax Field	(1/)	52.8	44	71.8	95	19.2	7	58.8	31	0	0

1/ 35 feet above ground.

The causes of local temperature and moisture distributions

The temperature and moisture distributions recounted in this paper are, for the most part, in accord with generally accepted principles of microclimatology (Geiger 1950). Radiation and air drainage are the dominant factors controlling local temperature distribution.

In an opening in the forest radiation controls the temperature differences; the trees around an opening break the wind and give heat radiation full play. A large opening, D/H = 2.0, is very subject to frost and extremes of high and low temperature (Geiger 1950). The sun shining in during the day makes the ground relatively hot, while outward radiation at night (the heat loss that makes nights cooler than days) makes such an exposed large opening relatively cool.

The site at Iowa-1 with a D/H of 1.0 (Station 4, table 3, page 18) approaches this condition. Even though it is on a north-slope shoulder, it has extremes of temperature equal to and at times greater than those in an open pasture on a southwest exposure. The small opening, D/H = 0.5 (Station 2, table 3), is not so open and does not have such extremes of temperatures. It loses heat at night faster than the surrounding woods (where trees prevent outward radiation) but it does not have as much heat loss as an open field. In the morning and evening the sun does not shine down into such an opening, but outward radiation continues. In this way the night period is extended and the cool period is much longer. After August 10 (the date varies slightly from year to year) the sun never shines down into an opening with a D/H of 0.5 at 43° North (Madison) so that the opening is always radiating heat outwards and receiving no direct sun radiation; hence, the opening is cool during the entire day.

The effect of a valley on temperature is mostly related to air drainage. Cold air is denser than warm air and tends to flow downhill, somewhat like water. Since it is less dense than water and friction effects are greater, the typical night temperature in a valley is cold in the bottom and warm on the shoulders of the slope as shown in figure 12.

The effect of the base of a slope is much like that of the valley. The cool, dense air drains down to the base of the slope and makes a cold-air pool.

A gentle slope has cool air pockets on it where the vegetation may make cold-air dams. The cool air draining down the slope could collect behind the dams. On steeper slopes the air drains onto the bottom of the slope.

In late June and early July when the sun is elevated 70° to 77° in the sky at noon, the radiation differences are minimized. The effect is pronounced through most of the teliospore season on ribes.

The role of moisture on leaves and the mechanics of its action are critical. In the studies described here, drier and wetter sites were found to influence rust distribution. Recently the radiant cooling of leaves to as much as 3.6° F. lower than the temperature of the air has been reported (Wellington 1950), and the condensation of moisture on such cooled leaves has been reported at relative humidities as low as 85 percent (Rogers 1957). In the latter case, snap-

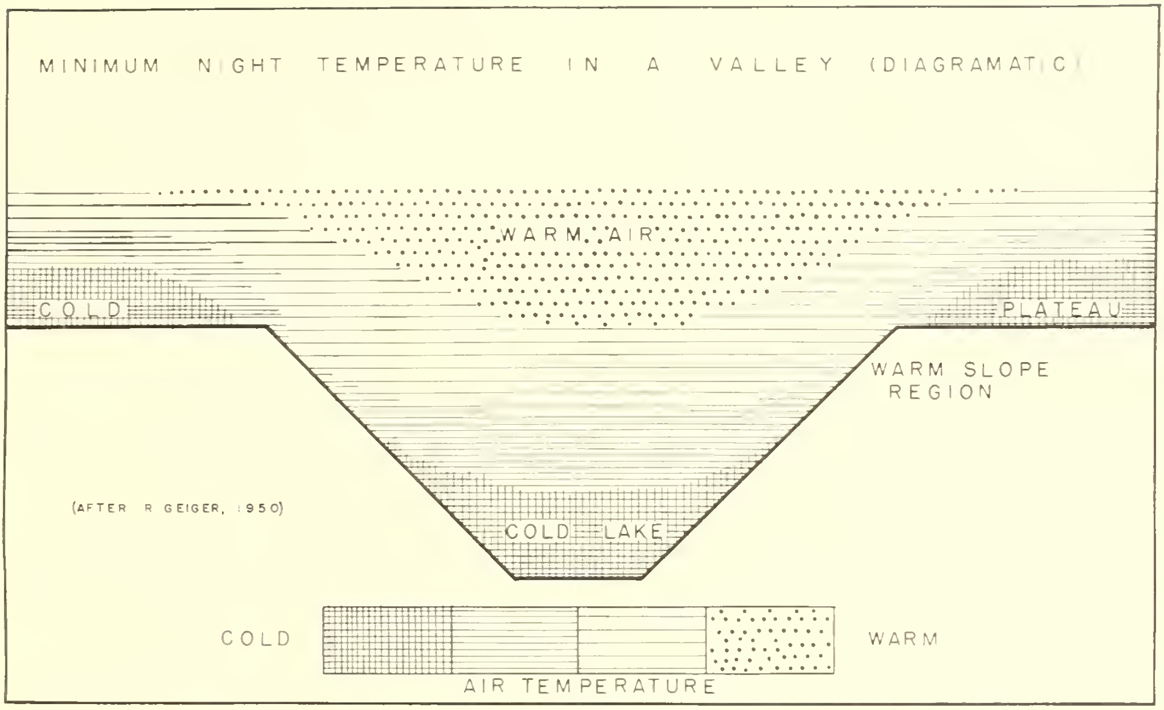

Figure 12.--The effect of a valley on night temperature.

dragon rust (Puccinia antirrhine D. & H.) infected its host at 85-percent relative humidity.

The limitations to the spread of rust under a closed canopy of tree crowns seemed to result from a lack of condensed moisture on leaves not exposed to the open sky. Such leaves did not cool, since outward radiation was reduced by the leaves above. In general, it was relatively dry under the tree canopy at night. The cooled layer of leaves in such a stand would be at the top of tree crowns, and this is where the moisture would condense.

A small opening in the forest had a surprisingly long wet period, presumably from the condensation on leaves in the opening during its long period of outward radiation when leaves are cooler than the air. The cool moist air draining into the opening from the tops of the surrounding tree canopy seems to add additional quantities of moisture to the air in the opening.

The local microclimatic effects are greater in the late summer and fall because the angle of the sun to the earth is more acute. The north slopes get proportionately less sun and the south slopes more; other related phenomena are also exaggerated.

Rust infection as correlated with temperature and moisture distribution

In preceding sections it was indicated that white pine blister rust in southern Wisconsin study areas was confined largely to openings in the crown canopy of the forest and to kettle holes, sheltered valleys, and the bases of slopes. It was also shown that these same sites were cooler (under the 68° F. critical for blister rust) and more moist for a longer period of time than the general area surrounding them.

As noted in the Introduction, it is assumed on the basis of previous work that in Wisconsin at least 2 weeks (or 1 week in September) with no more than 3 days over 82° (with a 5-hour warm period), followed by at least 48 hours of saturated air under 68°, is required for pine infection.

To find out if differences between sites were enough to be significant, the hygrothermograph records from various sites were searched for favorable cool and wet periods. According to records of September 5 to October 24, 1952, in Rock-1, the open kettle hole in which the moisture-temperature profile was made (Planting Area 7, fig. 3, page 6) had one chance for pine infection to occur (September 5 to 8). Up the slope about 20 feet at another weather station under a white pine cover there were no periods wet enough for pine infection. In the small opening at the other end of this small plantation, September 5-8 was cool enough and moist enough. Records at the nearest Weather Bureau Station (Madison), however, showed no periods wet enough for pine infection to occur during these 2 months. The two locations with favorable weather had some pine infection present when they were surveyed in 1951, but none was found on the slope.

In Iowa-1, during July and August of 1952, one period was cool and wet enough for pine infection at Station 1 (fig. 10, page 16), two periods were favorable at Station 2, and none was wet and cool enough at Stations 4, 5, and 6. Of the 52 pines at Station 1, 17 percent were infected; so were 35 percent of the 50 white pines at Station 2. Station 5 had one canker on one of the five trees. No pines were infected at Stations 4 and 6 or at any of the other four stations. Thus, the sites with rust present were also the ones with the cooler, more moist conditions favorable to infection.

The drier air under tree canopies, demonstrated in the Dane-1 area, indicates one of the reasons rust rarely was found under solid tree canopies within the State. In table 1 (page 11) the lowest percentages of plots with rust present in the west central upland and in northern Wisconsin were on tree-covered sites.

In an effort to correlate the pattern of blister rust infection on pine with macroclimate, a map showing the types of rust distribution in Wisconsin was prepared (fig. 1, page 4). The mean July temperature and the topography that influences the temperature were also mapped and superimposed on the rust distribution map (fig. 2). Topography is from Darley et al. (1948) and weather station elevations from the U.S. Weather Bureau (1954). The July averages of minimum and maximum temperatures given in the 1941 Yearbook of Agriculture (U.S. Dept. Agric. 1941) were used in constructing the isotherms. Since mean July temperature was found to be correlated with the larger topographic formations

and with elevation, the isotherms in the areas between the weather stations were modified to fit the topography of the land.

Figure 2 indicates that blister rust presence may be correlated with mean July temperature. Rust is generally present where the mean July temperature is less than 70° F. Rust incidence was high and rust had spread great distances from ribes in areas of Oneida County where the mean July temperature was 64°. In those regions where the mean July temperature was greater than 70° rust generally was uncommon and had a localized distribution, and where the mean was above 73° virtually no rust could be found.

Estimating the likelihood of blister rust infection on a given site

Refinements in estimating the probability of serious blister rust infection for any particular site would be valuable not only in ribes eradication work but in reforestation work as well.

The macroclimate records at Madison disclosed that weather cool enough for pine infection to develop seldom occurred in July and August but was confined almost entirely to September or October when most of the infected ribes leaves already had been lost through defoliation (Van Arsdel 1954). This general climate appears to be unfavorable for the spread of rust except in local areas. In this southern part of Wisconsin certain site factors could be arbitrarily valued. Where these values were combined they gave a fair approximation of the rust potential. In an initial attempt in this direction, certain numerical values were assigned to topographic and vegetative features as follows:

Topographic factors	Tentative value assigned[1/]
Special conditions	
Kettle holes	6
Sheltered valley	6
Position classes from figure 6 (page 8)	
Base of slope (1)	6
On the slope (2)	2
Shoulder of the slope (3)	-2
Flat (F)	0
Slope-percent classes from figure 6	
0-3 percent (1)	0
3-20 percent (2)	5
20-50 percent (3)	3
50-100 percent (4)	0
Over 100 percent (5)	-2
Vegetative-cover classes	
Covered with a complete crown canopy	0
Small opening (D/H = 1.0 or less)	9
Large opening or in the open (D/H greater than 1.0)	0
Brush (nondescript broken vegetation)	3

1/ For southern Wisconsin below 1000-foot elevation.

If all of the values pertaining to a particular site were added together and a sum of nine resulted, then blister rust very likely was present on pine. If the sum of the values was as high as 18, then serious damage to the pine might occur. The formula seems to apply in those parts of Wisconsin with mean July temperatures between 70° and 73° F. at elevations of less than 1000 feet above sea level (Van Arsdel et al. 1957).

While a sheltered valley cannot yet be defined closely, certain limits have been assumed. The Iowa-1 valley with a W/H (width to height) ratio of 2.0 and the Sauk-1 valley with a W/H ratio of 0.67 both had rust present. However, to the north of Iowa-1, where the valley was 923 feet across and 130 feet deep--W/H = 7.1--the pines were not infected. Sauk-2 was similar to Iowa-1 in that it had infected pine in a small north-facing valley, which led into a broad valley without infected trees. The large valley was about the same ratio as at Iowa-1. For present use a valley with a W/H ratio up to about 4.0 could be classed as sheltered. Valleys with a W/H ratio of 2.0 had much rust.

A small opening in the forest is here arbitrarily defined as an opening with a D/H (diameter to height of surrounding trees) ratio of 0.25 to 1.0. An opening with a D/H of 0.50 seems most favorable to the rust fungus.

The use of this additive formula may be illustrated by taking certain representative sites as they existed 20 years ago, examining their past history, applying the formula, and checking their present condition. For example, in 1931 in Rock-1, Planting Area 3 (fig. 3, page 6) was flat pastureland in the open, away from tree cover. The position value was 0, the slope value 0, and the vegetation value 0, so that the 1931 sum of the site factor values was 0. Ribes cynosbati and R. missouriense were abundant in the area as is often the case in old pastures in this region. White pines were planted in the area during 1935-40, and no blister rust was present on the pines in 1951. The use of the formula in the early 1930's would have shown a reasonable expectation that the pine would be rust free, and the expectation would have been realized. On the same farm, pines were planted in the small opening at Planting Area 5B (fig. 3) in 1935, as such planting is often recommended for filling in open places in the forest. Prior to this planting the site evaluation factors would have been: The land was flat, value 0; the slope-percent class was 1 (fig. 7, page 10), value 0; the vegetative-cover class was "in a small opening," value 9. Since the total value is 9, using this system, the 1935 prediction would have been for future blister rust infection. Eight trees were planted in the opening, and in 1951 four had blister rust cankers.

A 1932 evaluation of a small opening at the top of a north-facing bluff in Iowa-1 (fig. 4, page 7) would have resulted in a total value of 5: Shoulder of slope, a minus 2; slope of more than 100 percent, a minus 2; pines in a small opening, 9. A 1932 prediction for new trees seeding into the opening with the total evaluation of 5 would have been for no rust; the 1952 observations showed the trees to be rust free. Another excellent example was at Station 2 (figs. 4 and 11) in Iowa-1. In 1932 our total of site values would have been 26: Sheltered valley, 6; at the base of a slope, 6; in a small opening, 9; and on a class-2 slope, 5. Our 1932 prediction would have been for relatively heavy rust infection. Our 1952 survey showed that 35 percent of the 50 white pines had rust cankers.

Some areas did not have rust distributions that fit the additive formula. Certain more southerly areas, especially at lower elevations, had no rust where it

would have been expected from the formula; and the areas at higher elevations (more than 1000 feet above mean sea level) had more general rust distributions than the formula would indicate. The paucity of weather stations at the higher elevations limits our conclusions; but figure 2 shows that the summers are cooler at higher elevations. The more recently established weather station at Cashton with an elevation of 1380 feet shows cooler summers than would be expected from extrapolating curves comparing stations at lower levels. Thus the cooler conditions at the higher elevations, like those in more northerly locations, may contribute to greater rust presence.

Checking the accuracy of the formula

Of course, the formula fits the data from which it was derived (as the foregoing examples show), but it also applied to areas in southwestern Wisconsin which were sampled subsequent to the derivation. The sample consisted of 112 plots in 13 areas surveyed in 8 counties. These data, showing rust presence on various sites, are included in table 1 (page 11) along with the data from which the formula was derived. Of the 112 plots, 1 had rust present where the formula value was less than 9 (with expectation of no rust). The "miss" was located at the base of a slope. Twelve of the plots that had values of nine or more escaped rust; four of them had a marginal value of nine, and eight had less than five trees per plot and thus had extra chances of escape. Some of the 12 plots were in rust-free areas at lower elevations. The 89-percent total accuracy (99 out of 112 plots and only 1 percent "chance" infections) obtained with this formula in western Wisconsin indicates great promise in future development.

A Grant County area (Grant-1, fig. 1) was examined from an aerial photograph, and predictions were made as to the amount of rust on the additive site-formula basis. The predictions for 22 plots were subsequently checked by ground surveys. In this area there were no cases where rust occurred but had not been predicted. In three cases the formula indicated rust could be present, but none was found. The accuracy of prediction from aerial photographs in this small sample was 86 percent.

An approach using some sort of formula that would indicate rust possibilities seems to have enough merit to deserve a more intensive study. The additive formula can be improved by correction for elevations, by better sampling (including more trees per plot), and by more intensive studies in site types where sampling was meager. Some work has been started using average temperatures and elevation (Van Arsdel et al. 1957). A trial run using elevation data and average July temperature has been made. The correlation so far attained (shown in fig. 2) seems to offer considerable promise.

Summary

It had been noted that in certain large areas of southern Wisconsin where the alternate hosts were common and rust had been omnipresent on ribes bushes, the white pines were, nevertheless, generally free of infection. This study was undertaken to determine blister rust behavior on favorable and unfavorable sites and to provide a means for estimating the pine infection probability on a given site.

Individual trees examined in an area in Rock County (southern Wisconsin) with abundant ribes showed that the blister rust cankers occurred less than 5 feet above the ground. Cankers were limited to pine trees in openings in the forest canopy and in a kettle hole.

In systematic samples of white pine associated with ribes in southern and lowland western Wisconsin, blister rust was most often found in sheltered valleys. It occurred on 54 percent of the plots at the bases of slopes and 38 percent of those in small (D/H less than 1.0) forest openings. Larger openings and a closed forest had rust present less often. Only one-twentieth of the samples at the shoulders of slopes showed rust present.

A site formula based on the above factors was prepared. This predicted rust canker locations with 89-percent accuracy in southern and western Wisconsin at elevations below about 1000 feet in that area with an average July temperature of more than 70° F.

Studies of local variation in temperature and moisture distribution indicated that the bottoms of narrow valleys were under 68° F. for a longer period than level ground was, and that the shoulders of valleys were warm longer than either the valley or level ground. The bases of slopes were cool, somewhat like a valley, but the effect was less pronounced. A kettle hole averaged cooler than flat land sites. Openings in the forest with diameters less than the height of surrounding trees were under 68° longer than sites in the open or under the forest canopy.

High humidities were more common near the ground; the bottoms of narrow valleys had higher humidities, and kettle holes averaged more moist than flat land sites. Small openings in the forest were more humid and had saturated air more hours per day than did sites in the open field or in unbroken woods.

Northern Wisconsin had general blister rust distribution on pine with rust present on almost all sites. The lowest rust presence (68 percent of plots) was under tree canopy overstories.

There were indications that rust distribution was fairly well correlated with average July temperatures. As July temperature averages increased, rust became less common on the white pines. Rust was more general where July temperatures averaged less than 70°; where the average was higher, rust was usually confined to locally cool moist places.

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